F15/2*

Residual Stresses Associated with the Hydraulic Expansion of Steam Generator Tubing into Tubesheets

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INTRODUCTION

Westinghouse has used three different processes for full depth expansion of tubes into the tubesheets of recirculating nuclear steam generators: mechanical rolling, explosive expansion and hydraulic expansion. Each process aims to: (i) expand the tube tightly against the tubesheet, (ii) leave the smallest possible secondary side crevice depth, and (iii) minimize residual stresses in the expanded tube - all for the purpose of mitigating the effects of corrosion phenomena. The hydraulic expansion process was qualified and implemented in 1978. Since then over 1.1 million tube ends have been hydraulically expanded into production units. This paper summarizes the results of recent analytical studies relating to the residual stresses in the expanded tube.

BACKGROUND

The hydraulic expansion process is shown schematically in Figure 1. The tube is first tack expanded to a depth of about 3/4 inch by a urethane expansion process to facilitate welding of the tube to the cladding on the primary side face of the tubesheet. Following welding, the tube is hydraulically expanded through the full thickness of the tubesheet. A quick disconnect expansion gun (not shown) connects to the end of the expansion mandrel and supplies deionized water which passes through a hole down the axis of the mandrel and exits into the cavity between the tube and the mandrel. Pressurization of the water expands the tube. The pressure is held by O-rings that seal against polyurethane rings which in turn are squeezed against fixed metal rings. After the expansion, which takes only a few seconds, the water is withdrawn into the supply tank, the seals relax and the mandrel is easily removed. The hydraulic expansion equipment and tooling were developed for Westinghouse by Haskel, Inc. of Burbank, CA [1].

Figure 2 defines some important parameters of the expansion process. At Westinghouse, the tubesheet is about 22 inches thick and is made of a low alloy steel such as SA-508 Class 3. The tubing material is either Alloy 600 or Alloy 690 and is generally 11/16, 3/4 or 7/8-inch OD with a wall thickness in the range 0.040

SMiRT 11 Transactions Vol. F (August 1991) Tokyo, Japan, © 1991

to 0.050 inch. The radial gap (clearance) between the unexpanded tube and the tubesheet hole is nominally 0.005 to 0.008 inch. Though it takes less than 10,000 psi pressure to expand the tube into contact with the tubesheet, the pressure is increased into the range 30,000 to 40,000 psi, depending on the tubing and tubesheet dimensions and properties. The depth of expansion - or equivalently, the secondary side crevice depth - is controlled by the location of the urethane - metal ring interface relative to the secondary side face of the tubesheet. The crevice depth is less than 0.25 inch, typically 0.1 inch. The length of the transition zone between the expanded and unexpanded tube is about 0.25 to 0.35 inch.

The hydraulic expansion process is amenable to analytical modeling: the tube is uniformly expanded along its entire length with monotonically increasing pressure. There is no redundant work of deformation. Mechanical rolling, by contrast, is very difficult to model. The analytical work described in this paper calculates the contact pressure and the residual stresses in the tube for hydraulically expanded tubes. Unless noted otherwise, the calculations are made for the reference modeling parameters given in Table 1. The term strain hardening fraction describes the bilinear stress-strain curve and gives the ratio of the slope in the plastic range (tangent modulus) to the slope in the elastic range (Young's modulus). The term TSOD/TOD gives the ratio of the tubesheet simulant OD to the unexpanded tube OD for one of the models described in the text (a concentric cylinder).

CENTRAL REGION OF TUBESHEET

Several analytical models were used to assess the stresses in the tube and tubesheet ligaments in the central (mid-thickness) region of the tubesheet, i.e., away from end effects at the primary and secondary side surfaces.

<u>Finite Element Method.</u> The static inelastic option of the Westinghouse WECAN finite element computer code [2] was used to solve for the displacements, strains and stresses using the von Mises yield criterion and the associated Prandtl-Reuss flow rule. Computations were made for an isotropic hardening rule and for both plane-stress and plane-strain conditions. Two finite element models were used : (i) a quarter-symmetry model (Fig. 3) where the constraint of the adjacent tubesheet material was modeled by a row of elements with a reduced elastic modulus to achieve the appropriate stiffness, and the tube/tubesheet interface was modeled by non-linear gap elements; and (ii) a 5° slice through a plane-stress concentric cylinder model (Fig. 4).

<u>Theoretical Incremental Analysis.</u> Soler and Hong [3], Weinstock, Reinis and Soler [4], and Singh and Soler [5] have developed a theoretical incremental analysis which is very cost-effective for assessing the sensitivity of residual contact pressure to variations in tube and tubesheet geometrical and material property parameters. This is a plane-stress model of concentric cylinders which incorporates elastic/plastic behavior, isotropic strain hardening, von Mises yield criterion, large deformations, and temperature-dependent (time-independent) materials properties for evaluating thermal cycling effects. Calculations were made using a computer program provided by Soler.

Tubesheet Yielding and Residual Stresses. The WECAN quarter - symmetry model with plane-strain conditions was used to calculate the von Mises equivalent stresses in the tube and tubesheet ligament for expansion pressures of 30,35,40 and 45 ksi. Figure 5 shows the stresses at pressure and after unloading from 40 ksi. Localized plastic yielding of the tubesheet begins at the hole surface along the diagonal direction (Fig. 5 a) at an expansion pressure between 35 and 40 ksi. Even at 45 ksi pressure the plastic zone is quite small. The residual von Mises stresses remaining after removal of the pressure are shown in Figure 5 b. The residual stresses in the tube are essentially compressive hoop stresses which vary across the wall as shown in Figure 6.

Contact Pressure. The residual contact pressure between the tube and tubesheet calculated using the WECAN quarter-symmetry model varies with the angle theta around the circumference. The highest pressure occurs in the pitch direction (theta=0^o) and the lowest occurs in the diagonal direction (theta=45^o). Results for plane-stress conditions are shown in Figure 7. The average contact pressure around the circumference is used for comparison of results from different models. In using the Incremental Analysis Method, which is modeled by concentric cylinders, it is necessary to determine the OD of the tubesheet simulant cylinder which best models the stiffness of the actual tubesheet. For this purpose, three concentric cylinder simulations were analyzed as shown in Figure 8, where the outer diameter corresponds to either the minimum ligament (TSOD/TOD = 1.83), the maximum ligament (TSOD/TOD=3.0), or the average of the two (TSOD/TOD=2.42). Comparison of these results with those from the WECAN models shows that TSOD/TOD=2.42 adequately simulates the tubesheet. The contact pressures determined by all three models - WECAN quarter - symmetry, WECAN 5^o slice, and Incremental Analysis - are summarized in Table 2. There is good agreement between the results for all three plane-stress models. At the higher expansion pressures, the contact pressure for a plane-strain model of the tubesheet is about 10% lower than for a plane-stress model.

Sensitivity Analysis. Since the Incremental Analysis method provides a good measure of the average contact pressure for TSOD/TOD=2.42, it is a very cost effective means for assessing the effect of variations in various parameters on the contact pressure. Starting with the reference parameters in Table 1 for which the contact pressure is given in Table 2, Figure 9 shows the effect of changes in some of the more important parameters. The range shown for per cent change of a given variable is the range of uncertainty in the value of that variable (tube and tubesheet modulus, strain hardening fraction), or the range of practical control of the variable (expansion pressure, radial gap, tube yield stress). For given tube and tubesheet materials, the expansion pressure, radial gap and tube yield stress are the important variables subject to control which affect the residual contact pressure.

Temperature Effects. The tube/tubesheet joint (formed at room temperature) may be exposed to elevated temperatures during steam generator manufacturing, e.g. during post weld heat treatment (PWHT) of the tubesheet to channelhead weld seam. It is, of course, exposed to the temperatures and pressures appropriate to the steam generator service conditions. The WECAN 5^o slice and

Incremental Analysis concentric cylinder models were used to assess the effect of thermal cycles up to 1100°F on the contact pressure. Using published data (ASME Code, Section III, Division 1 Appendices) for the coefficients of expansion and elastic moduli, the parameters of Table 1, and neglecting creep, there is no loss of contact pressure (no plastic yielding of the tube) due to the thermal cycle for either Alloy 600 or Alloy 690. In an effort to assess the possible importance of creep, manual calculations were made using a creep constitutive equation for the tube material of the form:

$$\epsilon^{c} = \frac{Cpt}{1+pt} + \dot{\epsilon}_{m}t, \quad C = f(\dot{\epsilon}_{m}, t_{r}), \quad p = f(C, \dot{\epsilon}_{m})$$

where ϵ^{c} is total creep strain (%), $\dot{\epsilon}_m$ is minimum creep rate (%/h), t_r is time-to-rupture (h), and t is time (h). Using published creep data for Alloy 690 [6], the parameters in Table 1, and neglecting creep of the tubesheet (because the tubesheet ligament membrane stress is an order of magnitude less than the tube membrane stress), the predicted results are shown in Figure 10. In (a), the contact pressure at room temperature (or cold shutdown conditions) is shown after isothermal exposure to the indicated temperatures and times. Creep effects on residual contact pressure are insignificant below about 900°F. Part (b) of the figure shows the contact pressure after thermal exposure for the same condition and subsequent loading to normal operating conditions of 600°F and 1250 psi differential pressure.

TRANSITION ZONE

The residual stresses in the tube secondary side transition zone were evaluated with the ABAQUS [7] computer program and the axisymmetric finite element model shown in Figure 11. Interface elements with a coefficient of friction of 0.2 were used between the tube and tubesheet. The model predicts transition zone profiles and contact pressures as shown in Figure 12. The transition zone profile is representative of production practices. The contact pressures well within the tubesheet (zero for 30 ksi expansion pressure and 1460 psi for 40 ksi expansion pressure) are consistent with the previous results for the central region of the tubesheet. The narrow peaks of high contact pressure just inside the tubesheet lead to similar peaks in residual stresses.

The residual stresses were evaluated on both the ID and OD surfaces for expansion pressures of 30 and 40 ksi, tube yield strengths of 40, 50 and 60 ksi and radial gaps of 0.004, 0.008 and 0.012 inch. Figures 13a and 13b show the ID axial and hoop stresses, respectively. The peak residual tensile stresses are of particular interest. They occur near the expanded/unexpanded edge of the transition zone. The axial stress is higher than the hoop stress (by about 30 to 40%). The residual stress increases with increase in tube initial yield stress (residual axial stress is approximately 75-85% of tube yield stress), and, though not shown, the peak tensile stresses are hardly affected by the radial clearance or expansion pressure.

The OD axial and hoop residual stresses are shown in Figures 13c and 13d, respectively. The residual tensile stresses on the

OD are significantly less than on the ID. The peak tensile stress is an axial stress located near the last point of contact of the tube with the tubesheet. It is relatively insensitive to the expansion pressure, tube yield stress and radial gap and is about 10-12 ksi in magnitude.

DISCUSSION

There continues to be interest in the contact pressure between expanded tube and tubesheet and its connection with leak tightness and load carrying capacity of the tube-to-tubesheet joint. For nuclear steam generators the tube is welded to the tubesheet cladding. At Westinghouse, the weld is both a primary-to-secondary side leakage barrier and a load carrying weld capable of supporting the service loads. The primary purpose, therefore, for having a tight joint is to minimize ingress of secondary side fluid down the interface, thereby adding margin against crevice corrosion.

The contact pressure for hydraulically expanded tubes has been calculated by several analytical and theoretical techniques with reasonably self-consistent results. With reference to the expansion parameters considered, the Incremental Analysis method (plane-stress, isotropic hardening) of Soler and colleagues [3-5] is quite adequate for assessing the sensitivity of the contact pressure to variations in the parameters of the expansion process when an appropriate TSOD of the model outer cylinder is used (TSOD/TOD = 2.42). This contact pressure is about 10% lower for plane-strain modeling of the tubesheet but would not be affected by use of a kinematic hardening rule instead of isotropic hardening since there is no reverse yielding of the tube upon removal of the expansion pressure for either hardening rule.

Plastic yielding of the tubesheet ligament is insignificant for expansion pressures up to at least 45 ksi. Expansion pressures greater than 30 ksi are necessary to ensure a definite contact pressure. However, the absence of a calculated contact pressure does not necessarily mean that significant leakage will occur along the joint interface or that the pull out force is zero. For example, the present calculations predict no residual contact pressure and a small (0.0001 inch) radial gap for 30 ksi expansion pressure. Yet, even for 30 ksi expansion pressure, fluids typically penetrate only a short distance down the interface and high forces are required to pull the tube (not welded) out of the tubesheet. This is because the tubesheet holes are not perfectly smooth and geometrically perfect right circular cylinders; thus there exist local regions of intimate contact and geometrical (mechanical) interlocking of the tube in the tubesheet. In experiments with tubes expanded into thick tubesheets it has been difficult to establish good quantitative correlations between pull out force and contact pressure, particularly for assessing effects of thermal cycles on joint tightness. Sensitive helium leak tests suggest that elevated temperature exposure causes some relaxation of joint tightness, beginning with exposures above about 900°F. Since calculations which neglect creep show no relaxation of the contact pressure for exposures up to 1125°F, an effort was made to include creep effects. The results are tentative because of the lack of definitive constitutive equations, but they do suggest that creep may be a necessary condition for relaxation of the contact pressure.

During hydraulic expansion, the tube wall thins by about 0.0006 inch and the tube length shrinks by about 0.9% of the expanded tube length.

The calculated residual tensile stresses in the secondary side transition zone of the tube agree with qualitative results from stress corrosion cracking (SCC) experiments which show the location and orientation of the highest residual tensile stresses. Thus, both calculations and experiments show that: (i) the peak stress on the OD is an axial stress located near the last point of contact between tube and tubesheet, (ii) the peak stresses on the ID occur near the unexpanded edge of the transition zone where both the axial and hoop stresses are significant, with the axial stress being higher than the hoop stress for hydraulically expanded tubes, and (iii) the stresses are higher on the ID than on the OD. Of the variables which affect the residual stresses, and considering the likely range of each variable to be encountered in practice, the yield strength of the tubing is most important. Peak residual tensile stresses are proportional to the tube yield stress.

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6. Huntington Alloys: Inconel Alloy 690, 1980, Huntington Alloys, Inc., Huntington, West Virginia 25720, USA.
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Table 1. Reference Modeling Parameters*

Tube Size: OD 0.687 in., Wall tk 0.040 in.
Yield Str.: Tube 50 ksi, Tubesheet 60 ksi
Young's Modulus (10^6 psi):
Tube 30.3, Tubesheet 29.2
Strain Hardening Fraction: 0.015
Tube and Tubesheet
Coef. Thermal Exp. (10^{-6} in/in/$^{\circ}$F):
Tube 7.73, Tubesheet 6.41
Tubesheet Hole Square Pitch 0.98 in.
Expansion Pressure 40 ksi
TSOD/TOD 2.42
von Mises Yield Criterion
Prandtl-Reuss Flow Rule
Isotropic Hardening

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* Room Temperature Values

Table 2. Residual Contact Pressure (psi)

Analytical Method	Expansion Pressure, ksi 30	35	40	45
Plane Stress				
o WECAN 1/4 Sym	0	292	1505	2754
o WECAN 5° Slice	0		1493	
o Incremental Analysis				
TSOD/TOD = 3.0			970	
= 2.42	0	287	1492	2729
= 1.83			2800	
Plane Strain				
o WECAN 1/4 Sym	0	128	1320	2531
o WECAN 5° Slice			1365	

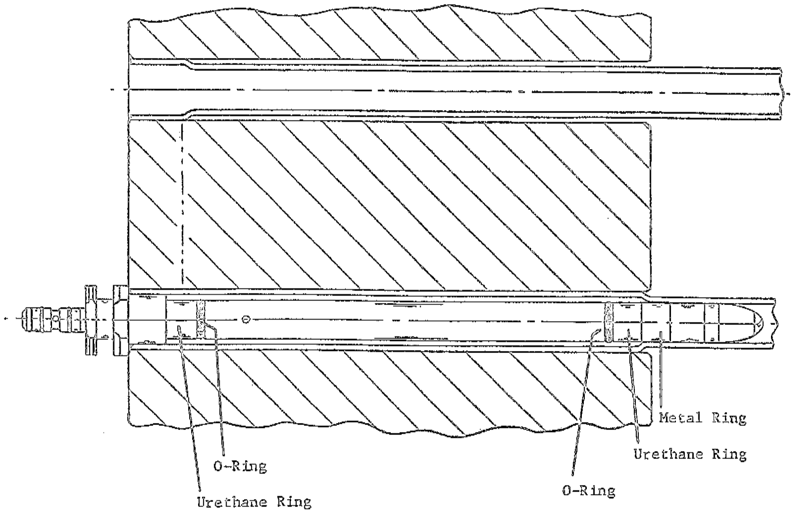


Fig. 1. Schematic of Tube Expansion Process

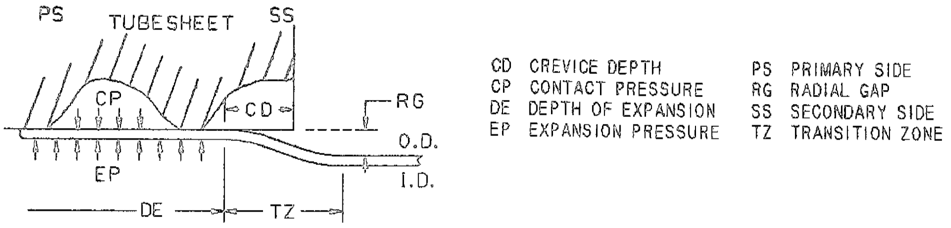


Fig. 2. Schematic of Expansion Parameters

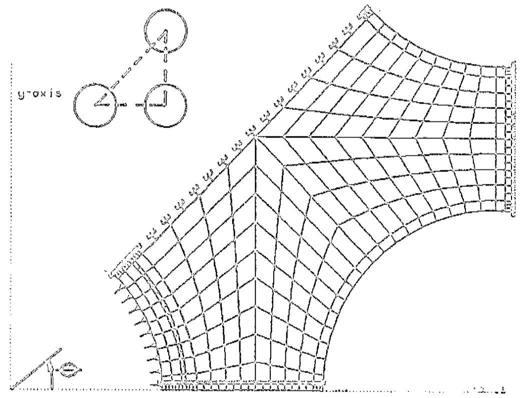


Fig. 3. Boundary Conditions for WECAN Quarter Symmetry Model

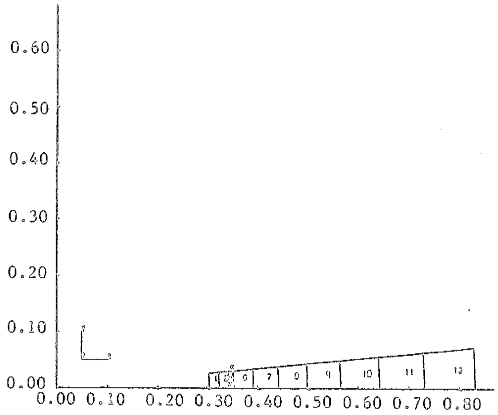
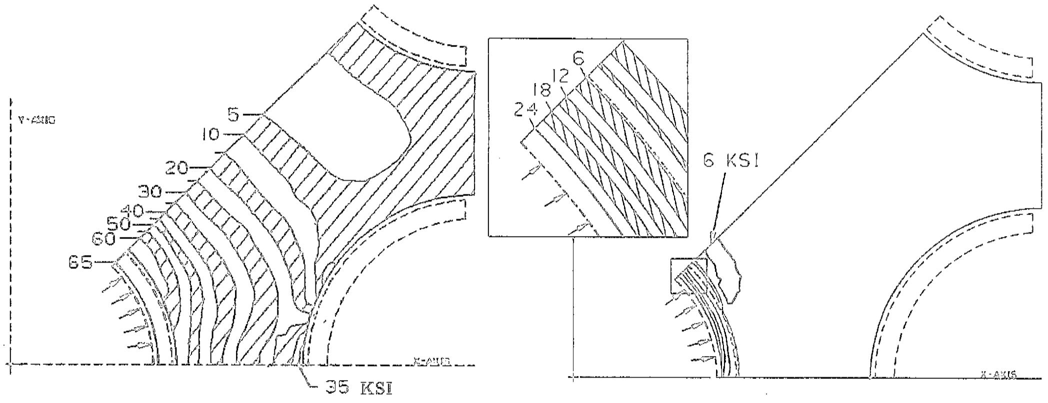


Fig. 4. Concentric Cylinder WECAN Model (5° Slice)



(a) At 40 ksi Pressure

(b) Pressure Removed

Fig. 5. von Mises Stresses in Tube and Tubesheet Ligament

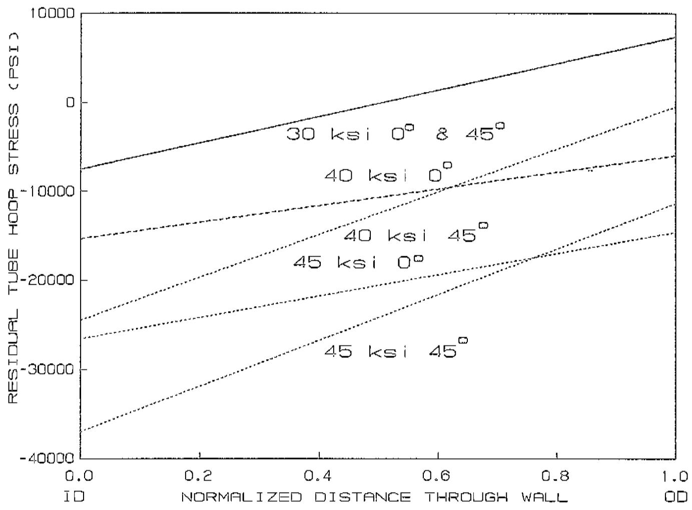


Fig. 6. Thru - Wall Residual Hoop Stresses

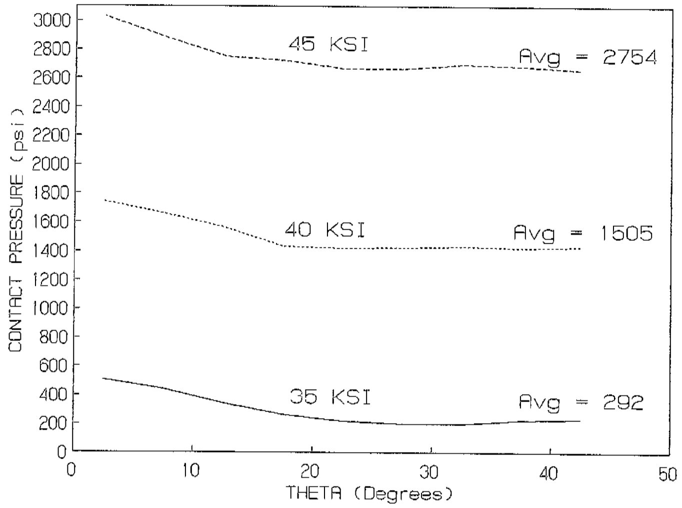


Fig. 7. Variation of Contact Pressure Around the Tube

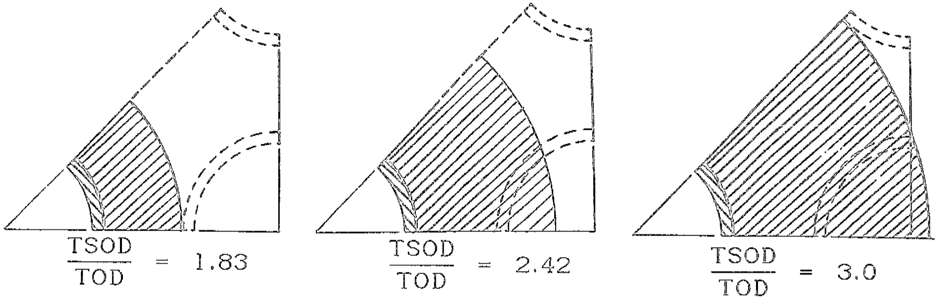


Fig. 8. Concentric Cylinder Simulation, TSOD/TOD Ratios

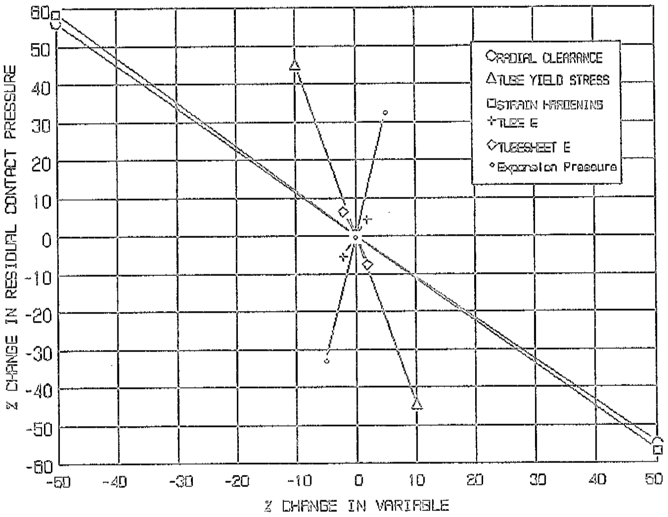


Fig. 9. Effect of Variables on Contact Pressure

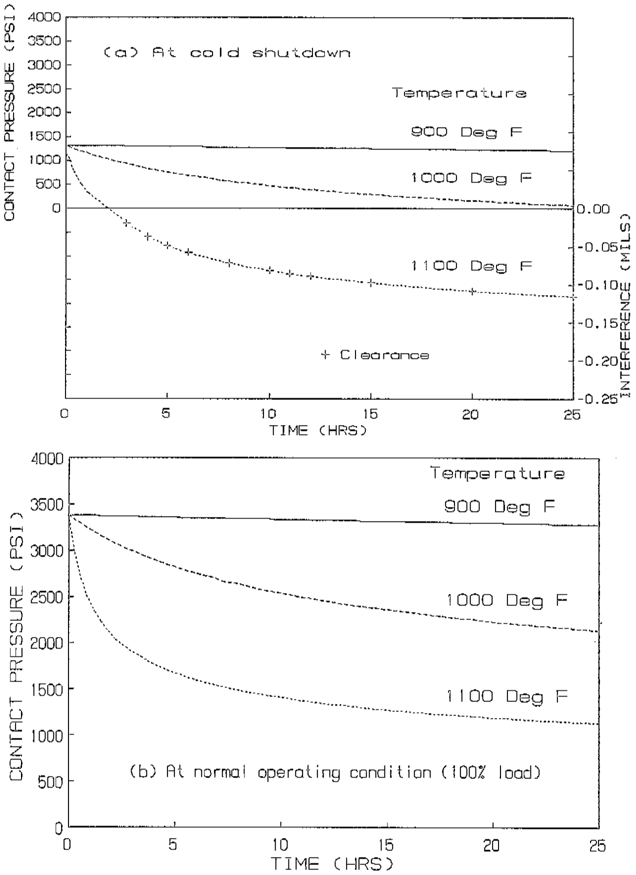


Fig. 10. Effect of Thermal Cycles, Including Creep, on Contact Pressure

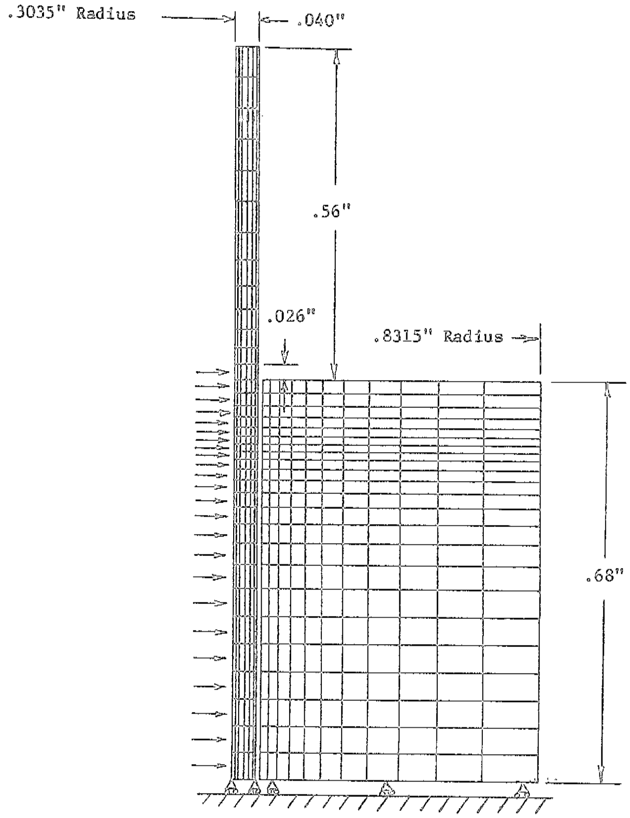


Fig. 11. ABAQUS Secondary Side Transition Boundary Conditions

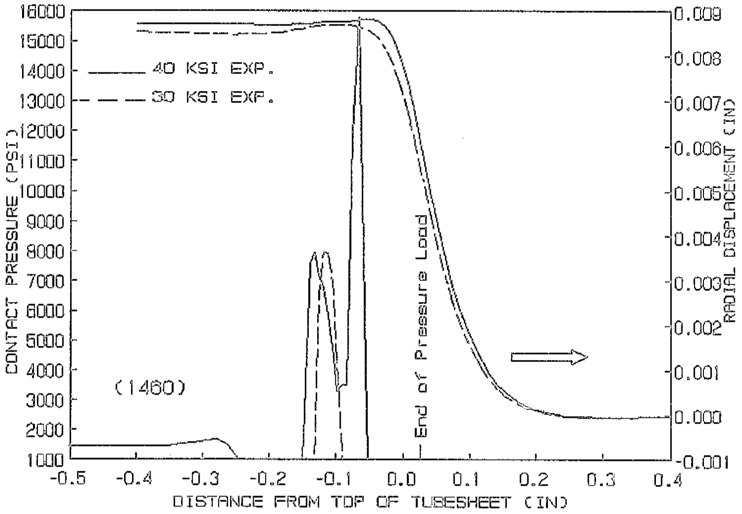


Fig. 12. Contact Pressure From ABAQUS Finite Element Model

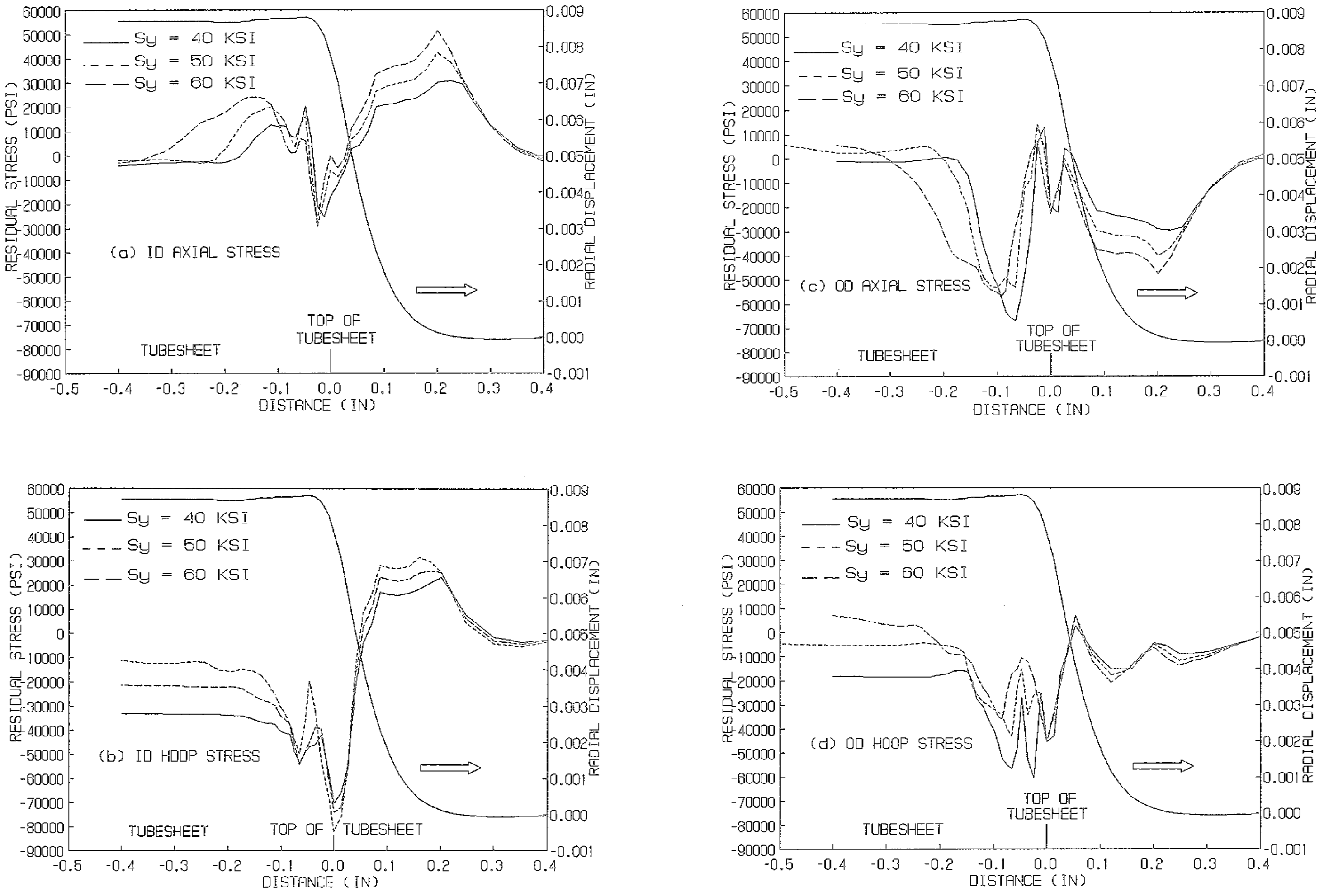


Fig. 13. Transition Zone Residual Stresses. (Tube Profile Shown for Sy = 50 ksi)